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Methane moving law with long gas extraction holes in goaf

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Abstract

In order to grasp the methane moving law in goaf and provide a theoretical data for gas extraction holes, the height of caving and fractured zones in the stope has been calculated according to the experiential formula and gas movement law has been observed by field and laboratory experiment. It also gives gas moving characteristics with different position of extraction holes. And it has the best gas extraction result when the final holes are arranged around 30m above the coal seam and 10-20m away from the tailentry in horizontal direction. Besides, the height of final holes should be adjusted to the overburden strata structure. When final holes are near the tailentry, their height should be controlled in the upper of regular caving zone; when they are close to the center of face, their height should be controlled at the bottom of fracture zones.

Keywords: gas in goaf; gas movement;gas extraction holes; position of extraction holes; experiment

1. Introduction

The roof strata above the goaf will fracture and form the caving, fracture and bending zones in the vertical direction after mining the coal seam. And there are lots of fractures and cracks in caving and fracture zones, the permeability of the stratum are also high. According to the “O” circle theory of fracture distribution in the stope [1], the gas of goaf will move and gather up along those fractures and cracks. Then it is easier to cause the gas exceeding the limit, which need to take measures to reduce gas content. In order to solve this problem and get the best extraction effect, the layout of holes should be adjusted to the rock structure changes according to the arch structure characteristics of roof strata’s movement [2].

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Gas in goaf will distribute after holes extraction. Therefore, the relationship between gas moving law and position of gas extraction holes should be studied so that gas in the corner of working face and goaf could be effectively controlled.

2. Hydrodynamics equations of gas movement

With the pressure gradient of roadways' ventilation, gas penetrates or diffuses to the goaf and then to roadways from the coal seam, and its flow velocity is very low which usually less than 10^{-5}m/s [3]. Therefore, the flow of gas and air in goaf belongs to low-speed category, and it hardly has an effect on the roadways' ventilation. Despite the pressure gradient is very high, the gas and air flow in the mined-out area and roadways can still be regarded as the incompressible flow [4]. Besides, the distribution of rock, fractures and cracks in goaf are irregular. Consequently, the gas movement in the fractured rock of goaf is taken for continuum medium movement in pore medium [5].

2.1. Gas Seepage characteristics

Goaf is regarded as porous medium in the research; the source item of fluid momentum loss is described as the following equation [5].

$$S_i = -(\sum_{i=1}^{3} D_{ij}\mu v_j + \sum_{i=1}^{3} C_{ij}\frac{1}{2}\rho|v|v_j) \tag{1}$$

In equation 1, S_i is the source of momentum equation of the number i (x, y or z), μ is the viscosity of molecular, D and C are predefined matrices, $|v|$ is vectors module of velocity, and v_j is the velocity component of the source in x, y or z direction.

Generally, the pressure drop is proportional to the velocity in the low laminar flow of porous medium. The porous medium model could be simplified by using Darcy characteristics when the liquid inertial loss is ignored.

$$S_i = -\frac{\mu}{\alpha} v_j \tag{2}$$

In equation 2, α is the permeability for expressing the space and the function of preventing the viscosity, m^2.

2.2. Gas diffusion characteristics

There are two main controlling factors for the gas movement in the goaf. One is the molecular diffusion caused by the concentration and thermal gradient. Another is viscous flow or mass flow on the action of pressure gradient. According to the Fick characteristics, the following formula is the diffusion equation [4].

$$J_i = \rho D_{im}\frac{\partial X_i}{\partial x_i} - \frac{D_i^T}{T}\frac{\partial T}{\partial x_i} \tag{3}$$

In equation 3, J_i is the gas flow caused by the concentration and thermal gradient; D_{im} is the diffusion coefficient of mixed gas; X_i is the mass fraction of i gas; D_i^T is the thermal diffusion coefficient; and T is the temperature. When the gas concentration is much higher, equation 7 could be taken place by the diffusion formula of multicomponent.

$$J_i = \rho \frac{M_i}{M_{mix}} \sum_{j,j \neq i} D_{ij} \left(\frac{\partial X_j}{\partial x_i} + \frac{X_j}{M_{mix}} \frac{\partial M_{mix}}{\partial x_i} \right) \tag{4}$$

In equation 4, if the gas is i or j, M_i is its molecular weight, D_{ij} is the multicomponent diffusion coefficient of the No. i gas component in the gas, and M_{mix} is the molecular weight of mixed gas.

2.3. Control equations of gas

The gas emission and movement has close relationship with the air flow condition in gob, and it belongs to the typical permeation-diffusion process. Because the gas flow in goaf is regarded as the incompressible flow, control equations of flow field can be replaced by the Navier-Stocks equation [6, 7].

$$\frac{\partial(\rho Y_s)}{\partial t} + \frac{\partial}{\partial x_j}(\rho Y_s u_j) = \partial(\rho D_s \frac{\partial Y_s}{\partial x_j}), \quad (s=1, 2, \ldots, n_s) \tag{5}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j + \delta_{ij} p) = \frac{\partial \tau_{ij}}{\partial x_j} + S_i \tag{6}$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial}{\partial x_j}(\rho H u_j) = \frac{\partial}{\partial x_j}(\tau_{ij} u_j + k \frac{\partial T}{\partial x_j}) \tag{7}$$

$$p = \rho T R_u \sum_{s=1}^{n_s} \frac{Y_s}{M_s} \tag{8}$$

In formulas, ρ is mixture density, g/m; T is time variable; u_i and u_j are velocity, m/s; δ_{ij} is "Kronecker delta"(when $i=j$, $\delta_{ij}=1$; if not, $\delta_{ij}=0$); P is pressure, Pa; τ_{ij} is shear stress tensor of molecular; S_i is the source item of momentum loss to express pore medium; E is the energy in per volume, J; H is total enthalpy in per volume, J/mol; k is the heat transfer coefficient of fluid; T is static temperature, K; n_s is the sum of components; R_u is universal constant, and it is 8.3145 J/(mol • K); if the component is s, M_s is its molecular weight, Y_s is its mass concentration; D_s is its mass diffusion coefficient, and h_s is its absolute enthalpy value of unit mass.

In control equations, equation 5 is the continuum equation of each component, equation 6 is the momentum equation of mixtures, equation 7 is the energy equation of mixtures, and equation 8 is the state equation of ideal gas of mixtures.

3. Field observation

3.1. Working face situation

Synthetic mechanized longwall mining technology and fully caving method for managing mined areas are used in Chengshan mine. The main coal seam is the No.3B coal seam, and it's average thickness is 3.0m, average dip angle is 8° . And the coal reserves are 600,000t. No.3202 working face of Chengshan mine is 600m along the mining direction and 240m along sloping direction. During drifting the headentry of No.3202 working face, the highest absolute gas emission is even 9.3m^3/min, and it is 41.6m^3/min during mining the working face. Therefore, gas emission is much higher in this coal mine. It is difficult to solve the problem only by ventilation measures. Gas extraction technology is one of the best measures for controlling gas content in the goaf. According to the “O” circle theory of fracture distribution in the stope, gas will move and gather up in the fractures of “O” circle in the goaf. In order to study the range of roof strata and provide the reasonable parameters for gas extraction, the height of roof-falling and fractured zones in the stope is calculated according to the experiential formula [8].

$$H_1 = M / [(K-1)\cos\theta] \tag{9}$$

$$H_2 = 100M / (1.6M + 3.6) \pm 5.6 \tag{10}$$

In equation 9 and 10, H_1 and H_2 are the height of roof-falling and fractured zones along the normal direction of the coal seam separately; M is the height of the mining coal seam; K is the broken coefficient of rock in roof-falling zones which is 1.2; and θ is the dip angle of the coal seam. Then H_1 is equal to 15.15m, and H_2 is 30.11-40.31m.

3.2. Observation method

Sensors are used to monitor and observe gas distribution in goaf and extraction holes respectively. When the working face advances about 80m from the interconnection, the first head of sensors are installed along the tailentry and headentry, which are numbered T1and T4 separately, and it is the first field. Then, the working face goes on advancing 200m and 300m from the interconnection, four sensors are installed along the tailentry and headentry respectively, which they are respectively numbered T2, T3, T5, T6. Sensors of extraction holes are installed in the number 1, 3, 6 holes of the second and third holes field, and they are numbered T2-1, T2-3, T2-6 and T3-1, T3-3, T3-6. Besides, T2-1 and T3-1 are inserted into 120m along the holes; T2-3 and T3-3 are inserted into 80m along the holes; and T2-6 and T3-6 are inserted into 40m along the holes. Figure 1 shows a sketch of the arrangement of gas monitor sensor in No.3202 working face. In figure 1, only the first head of sensors and the second field are indicated.

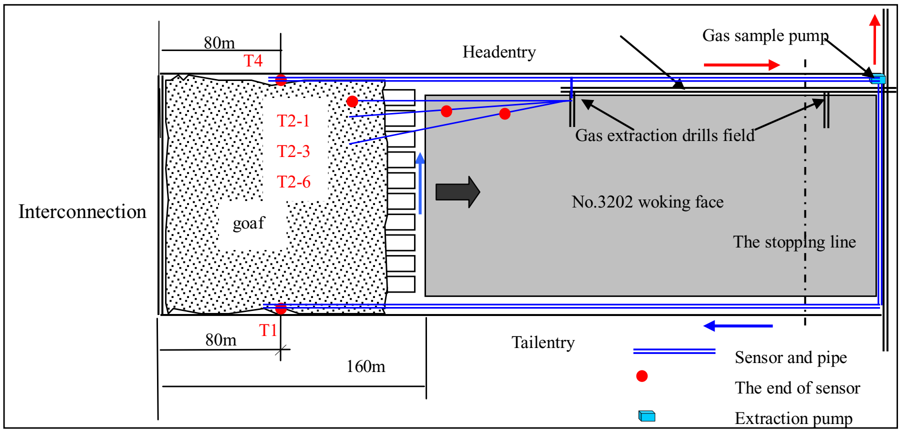


Fig.1 Arrangement of gas monitor sensor in No.3202 working face

3.3. Observation results

Observation results are shown in figure 2. Gas concentration increases in the goaf with the rising of distance from working face. When the distance from the working face is less than 150m, the change of gas concentration will relatively stable. For example, when the distance from the working face to the observation point is 10m, 50m, 100m and 150m, the average gas concentration is 2.6%, 3.9%, 4.1% and 5.9% separately. But if the distance is more than 150m, gas concentration increases sharply. Gas concentration reaches 10.55% if the distance from the working face is 170m; it is even much more than 16.9% when the distance is far more than 200m. Sensors monitoring result indicates that there exists a huge gas storeroom in the goaf, and the farther the distance from the working face to observation points, the higher the gas concentration gathering up.

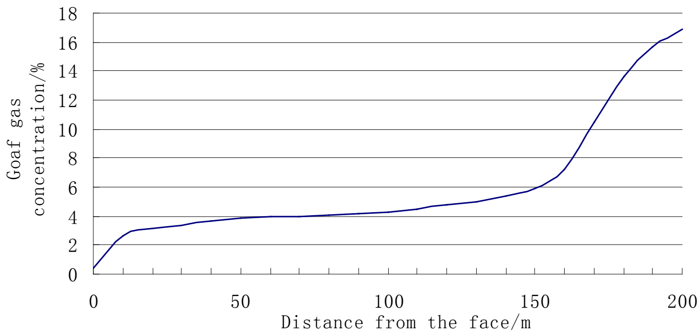


Fig.2 Changing curve of goaf gas average concentration

4. Laboratory experiment

With the influence of construction technology, the monitoring effect of gas distribution near tailentry is much better by using sensors monitoring system in the goaf. But it is difficult to monitor the middle and bottom of the goaf, particularly, it is difficult to know gas distribution well in different holes position. Therefore, the equivalent material simulation is done in the laboratory. The experiment has been done by using integrated simulation table on gas and rock movement which was developed by China University of Mining & Technology, Beijing. The experimental model is shown in figure 3.

Fig.3 Integrated simulation table on gas transporting and rock moving

4.1. Experimental details

The geometry similarity ratio of the model is 1:100, and the integrated simulation table has four reticular test systems in which there are 320 sampling points. Meanwhile, every sampling point links to a suction pump. Long holes are used to simulate gas extraction in the field, which are also arranged above the tailentry. Besides, the vertical distance above the tailentry is 20cm, 30cm and 40cm respectively, and the horizontal interior distance from the tailentry to holes is 10cm when the vertical distance is 20cm, and it is 10cm, 20cm and 30cm respectively when the vertical distance is 30cm. The extraction flow of holes is 0.4ml/min, the dry bulb temperature is 15.2℃, the wet bulb temperature is 14.2℃, the relative humidity is 90%, and the velocity pressure of return air is 2.192mm water column.

According to the position of extraction holes, there are six testing programs, and experimental results are shown in figure 4. In figure 4, *H* stands for the horizontal interior distance from the tailentry to gas extraction holes, and *V* stands for the vertical distance above the tailentry between gas extraction holes and the tailentry.

I: The experiment does not use gas extraction in goaf, and its distribution of gas concentration is shown in figure 4(a).

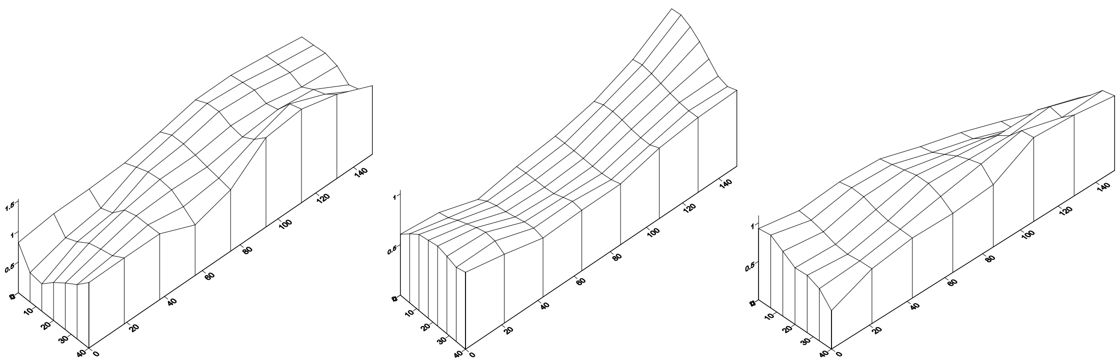
II: The experiment uses gas extraction holes in goaf. The vertical distance is 40cm, and holes are parallel with the tailentry. The distribution of gas concentration is shown in figure 4(b).

III: The vertical distance above the tailentry is 20cm, and the horizontal interior distance is 10cm. The distribution of gas concentration is shown in figure 4(c).

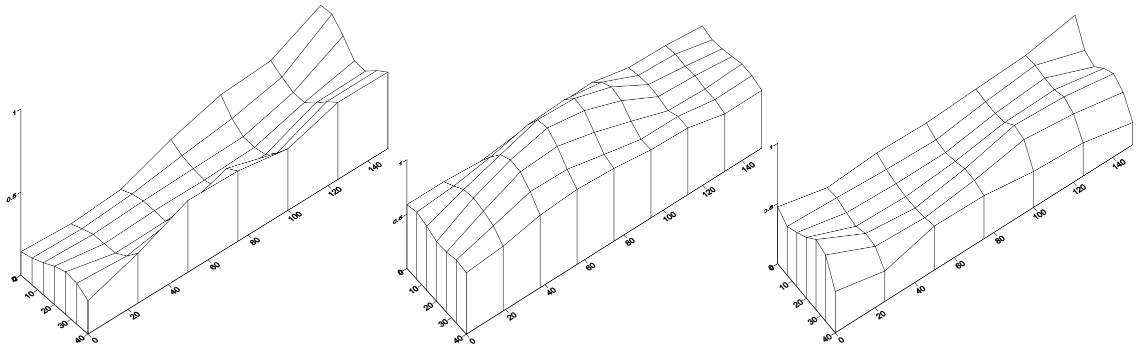
IV: Gas extraction holes are over the tailentry, and the vertical distance is 30cm. The distribution of gas concentration is shown in figure 4(d).

V: The vertical distance is 30cm, and the horizontal interior distance is 10cm. The distribution of gas concentration is shown in figure 4(e).

VI: The vertical distance is 30cm, and the horizontal interior distance is 20cm. The distribution of gas concentration is shown in figure 4(f).



(a) Gas distribution in goaf before extraction (b) *V*=40cm, *H*=0cm (c) *V*=20cm, *H*=10cm



(d) V=30cm, H=0cm (e) V=30cm, H=10cm (f) V=30cm, H=20cm

Fig.4 Gas distribution in goaf with different extraction parameters

4.2. Experimental results

When the experiment does not use gas extraction in the goaf, the gas concentration is less than 1% near the intake side or even lower, but there is gas of high concentration flowing into the working face near the tailentry side, and the distribution of gas concentration is veined shape in the middle of the goaf. When the experiment is taken II program, the gas concentration reduces integrally in the goaf, but the gas concentration is more than 1% in the upper corner of the tailentry. When the experiment is taken III program, the change of gas concentration is not obvious integrally in the goaf, but the concentration near the tailentry decreases. When the vertical distance above the tailentry is 30cm, the gas concentration all reduces in goaf. When the program is IV, the reduction is obvious near the intake side and gas concentration is less than 0.5%, but it still maybe beyond 1% near the tailentry. When the experiment is taken V program, gas concentration obviously decreases near both intake and tailentry side, but gas concentration is around 1% in the middle of goaf, which is much higher. When the experiment is taken VI program, the whole gas concentration in the goaf reduces obviously; it is around 0.5% in the middle of intake and goaf, but gas gathers up in the upper corner of the woking face.

Comparing with all experiments, it is easy to know the follwing views.

- The position of gas extraction holes has a great effect on gas concentration in the goaf. In the vertical direction above the tailentry, the lower the position of holes, the worse gas extraction results, and gas concentration is limited in return air side of working face. But when the gas extraction holes lay out in high position, gas concentration obviously reduces in return air side. And the extraction result is the best when the vertical distace above the tailentry is 30cm. Besides, if gas is extracted in the top of tailentry, gas concentration will reduce on a large scale. But it is still high in the upper boundary of goaf and it is possible to gas up in the upper corner of working face.
- With the same vertical distance and same gas extraction volume, holes are moved little distance into working face when the horizontal interior distance over the working face is 10cm and 20cm respectively, while the controlling range changes largely. If holes are too close to the tailentry, though the whole gas concentration reduces obviously in the back of goaf, gas concentration is high near the tailentry, and it is possible to gas up in the upper corner of working face. And if the horizontal interior distance is too far, it is also apt to gas up. In order to reduce the whole gas concentration in the goaf and near the tailentry, and deal with gas in the upper corner of working face, gas extraction holes

should be located over the working face and the reasonable horizontal interior distance from tailentry to holes is 10-20m.

Therefore, gas extraction holes should be located above the rock-falling zones and at the bottom of fracture zones as much as possible according to the collapsed state of roof strata. And it is fanshaped for all holes. The height of final holes is different in different position. The height of final holes near the tailentry is about 20m above the regular rock-falling zone; the height of final holes near the middle of goaf is about 30m at the bottom of fracture zone. And the reasonable horizontal interior distance from tailentry to gas extraction holes is 10-20m.

5. Conclusions

Gas movement in the fractured rock of goaf can be regarded as the incompressible flow in the pore medium, and its moving state is closely related to the airflow. The molecular diffusion and viscous flow (or mass flow) are two main forms of the gas movement in the goaf. And the control equations of flow field can be replaced by the Navier-Stocks equation.

Field observation indicates that gas concentration increases in the goaf as the distance from the working face to observation point rises. When the distance from the back of goaf to the working face is far beyond 150m, its gas concentration is much higher than near the working face. And there exists a huge gas storeroom in the goaf, in which gas has extraction value.

In order to reduce the gas concentration in the goaf and the upper corner of working face, gas extraction holes should be loacted according to the collapsed state of roof strata, which is based on the experimental results. Therefore, holes should be arranged to fanshaped pattern as much as possible. The height of final holes near the tailentry is about 20m above the regular rock-falling zone; the height of holes near the middle of goaf is about 30m at the bottom of the fractured zone. And the reasonable horizontal interior distance from tailentry to observation point is 10-20m.

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